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USING INDICATORS OF STOCK STATUS WHEN TRADITIONAL REFERENCE POINTS ARE NOT AVAILABLE: EVALUATION AND APPLICATION TO SKIPJACK TUNA IN THE EASTERN PACIFIC OCEAN

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1. INTRODUCTION

A major management objective for tunas in the eastern Pacific Ocean (EPO), is to keep stocks at levels capable of producing maximum sustainable yields (MSYs). Management objectives based on MSY or related reference points (*e.g.* fishing mortality that produces MSY (F_{MSY}); spawner per recruit proxies) are in use for many species and stocks worldwide. However, these objectives require the availability of the reference points and quantities that they are compared to. The various reference points require different amounts and types of information, ranging from biological information (*e.g.* natural mortality, growth, and stock-recruitment relationship) and fisheries characteristics (*e.g.* age-specific selectivity) to absolute estimates of biomass and exploitation rates. Absolute estimates of biomass and exploitation rates generally require a formal stock assessment model. For many species, the information required to estimate these quantities is not available, and alternative approaches are needed. Even more data are required if catch quotas are to be used as the management tool.

Skipjack tuna is notoriously difficult to assess. Due to skipjack's high and variable productivity (*i.e.* annual recruitment is a large proportion of total biomass), it is difficult to detect the effect of fishing on the population with standard fisheries data and stock assessment methods. This is particularly true for the stock of the EPO, due to the lack of age-frequency data and the limited tagging data. Skipjack's continuous recruitment and rapid growth mean that the temporal stratification needed to observe modes in length-frequency data make the current sample sizes inadequate. Previous assessments have had difficulty determining the absolute levels of biomass and exploitation rates, due to the possibility of a dome-shaped selectivity curve (Maunder 2002; Maunder and Harley 2005; Figures 1 and 2). A dome-shaped selectivity curve would mean that there is a cryptic biomass of large skipjack that cannot be determined. The most recent assessment of skipjack in the EPO (Maunder and Harley 2005) is also considered preliminary because it is not known whether catch per day fished for purse-seine fisheries is proportional to abundance. The results from the most recent assessment are more consistent among sensitivity analyses compared to the earlier assessments (*e.g.* Figures 1 and 2), which suggests that they may be more reliable than the previous assessments. However, in addition to the problems listed above, the levels of age-specific natural mortality are uncertain, if not unknown, and current yield per recruit (YPR) calculations estimate that YPR would be maximized by catching the youngest skipjack in the model (Maunder and Harley 2005). Therefore, neither the biomass- or fishing mortality-based reference points or the indicators to which they are compared are available for skipjack tuna in the EPO.

One of the major uncertainties mentioned above is the uncertainty as to whether the catch per unit of effort (CPUE) of the purse-seine fisheries is an appropriate index of abundance for skipjack, particularly when the fish are associated with fish-aggregating devices (FADs). Purse-seine CPUE data are particularly problematic because it is difficult to identify the appropriate unit of effort. In the current assessment, effort is defined as the amount of searching time required to find a school of fish on which to set the purse seine, and this is approximated by number of days fished. Few skipjack are caught in the longline fisheries or dolphin-associated purse-seine fisheries, so these fisheries cannot be used to develop reliable indices of abundance for skipjack. Within a single trip unassociated purse-seine sets are generally intermingled with floating-object or dolphin-associated sets, complicating the CPUE calculations. Maunder and Hoyle (2007) developed a novel method to generate an index of abundance, using data from the floating-object fisheries. This method used the ratio of skipjack to bigeye in the catch and the "known" abundance of bigeye based on stock assessment results. Unfortunately, the method was of limited usefulness, and more research is needed to improve it. Currently, there is no index of relative abundance that is considered to be reliable for skipjack in the EPO. Therefore, other indicators of stock status, such as the average weight of the fish in the catch, should be investigated.

Since the stock assessments and reference points for skipjack in the EPO are so uncertain, development of alternative methods to assess and manage skipjack that are robust to these uncertainties would be beneficial. Full management strategy evaluation (MSE) for skipjack would be the most comprehensive method to develop and test alternative assessment methods and management strategies (Maunder 2007). Unfortunately, developing MSE is time-consuming and has not yet been conducted for skipjack. In addition, higher priority for MSE is given to yellowfin and bigeye tuna, as available data indicate that these species are more vulnerable to overfishing than is skipjack. Therefore, we investigate some simple indicators of stock status based on relative quantities. Rather than using reference points based on MSY, we compare current values of indicators to the distribution of indicators observed historically.

2. METHODS

To initially explore which indicators may provide good relative measures of the status of the stock, we compare the indicators to the relative exploitable biomass and relative exploitation rates from the most recent stock assessment (Maunder and Harley 2005). The annual relative exploitable biomass is defined as the sum of the numbers at age estimated from the stock assessment multiplied by the weight at age and the average fishing mortality at age. Weighting by the average fishing mortality at age places emphasis on ages that are caught. This is calculated for each month of the year and then averaged. The average fishing mortality at age is calculated from the stock assessment estimates over the 1993-2003 period. The annual exploitation rate is calculated as the total catch in a year divided by the annual exploitable biomass for that year. The indicators, which are based on data, are catch, catch per day fished for each of the floating-object and unassociated purse-seine fisheries (Maunder and Harley 2005: Figure 2.1), average weight, and standardized effort. The standardized effort, which is a measure of exploitation rate, is calculated as the sum of the effort, in days fished, from the floating-object and unassociated fisheries. The floating object-effort is standardized to be equivalent to the unassociated effort by multiplying by the ratio of the average floating-object CPUE to the average unassociated CPUE. It should be noted that all of these quantities are used in the stock assessment model. The average weight is calculated from the length-frequency data that are used in the stock assessment. The catch and effort data that are used to generate the CPUE are also included in the stock assessment model, using a method that is consistent with including the CPUE as an index of abundance in the assessment. Therefore, these comparisons are not independent, but are nonetheless informative.

To evaluate the current values of the indicators in comparison to historical values, we use reference levels based on adding or subtracting 1.645 standard deviations, based on the variation in the time series, to the average of the time series. This includes, on average, 90% of the historical values. Values outside these reference levels could be considered undesirable, but which reference level is best depends on the indicator (Table 1). The 90% value is somewhat arbitrary, but should be a reasonable guide. We also present the 5th and 95th percentiles, as the distributions of the indicators are somewhat asymmetric.

Next, we take the most recent data, including data for 2006, and use the methods described above to evaluate the current relative status of the stock of skipjack in the EPO. We also expand the average weight data back before the start of the stock assessment (1975), but, due to the expansion of the fisheries during this time, the earlier data are problematic.

Finally, we develop a simple stock assessment model to investigate the relationship between the CPUE and average weight data (Appendix). The population was modeled from 1975 to 2006. The model is age-structured to allow calculation of average weight. The von Bertalanffy growth curve is used to model length at age. The estimated average length of the fish of the first age class represents the length at recruitment to the fishery. Catch is taken out of the population at the start of the year. Initial numbers at age, annual recruitment, and a constant natural survival are also estimated. Age four is used as a plus group in the model. The parameters of the von Bertalanffy growth curve and the weight-length relationship are fixed (L_∞= 84.6cm, K = 0.8, α = 0.5529x10^{-5}, β = 3.336). The model is fitted to the two CPUE time series and to the average weight data. Log-normal likelihood functions with standard deviations fixed at 0.3 are used for all three data types to give equal weight to each. The average weight is used as an absolute index, while the CPUEs are used as relative indices. A maximum exploitation rate constraint was set at 0.9.

3. RESULTS

In general, the exploitable biomass estimated in the most recent assessment follows the trend in the CPUE data (Figure 3). The trend is closer to the CPUE for the unassociated fishery (R-square = 0.42) compared to the floating-object fishery (R-square = 0.33). The average weight data also show a pattern similar to the biomass trend, but are lagged by one year (R-square = 0.67; *i.e.* average weight in year y + 1 is correlated with exploitable biomass in year y). The standardized effort data shows the same large decline after 1981 and subsequent increase as the exploitation rate estimated by the stock assessment (Figure 4). However, they differ for the first few years and peak in about 1989.

Catch, CPUE, and exploitable biomass were above or near the upper reference level (based on + 1.645 standard deviations of historic levels) in 2003 (Figure 3). Exploitation rate and average weight were around the average. These results suggest that there was no reason for management concern for skipjack tuna in the EPO in 2003. The indicators never surpass the appropriate reference level considered to be undesirable. This is because the standard deviation is influenced by spikes in the indicators, indicating that asymmetric reference levels, such as percentiles, may be more appropriate. Reference levels based on percentiles produce similar conclusions about the status in 2003 to those based on standard deviations (Figure 5). However, the standardized effort indicator of exploitation rate in 2003 was above the upper reference level (Figure 4).

Figures 6, 7, 8, and 9 show the calculated indicators average weight, CPUE, standardized effort, and catch. The average weight for skipjack has been declining since 2000, and the 2006 average weight is approaching the lower reference level (Figure 6). However, the CPUEs for both floating-object and unassociated fisheries have generally been increasing since 2000 (Figure 7). The unassociated CPUEs in 2005 and 2006 are above the upper reference levels. The standardized effort indicator of exploitation rate has been increasing since about 1991, and in 2006 is above the upper reference level (Figure 8). There is an apparent contradiction between the recent CPUE increase and the changes in the standardized effort (increase) and average weight (decrease) indicators for skipjack tuna in the EPO. This is true even when the one-year lag for average weight is taken into consideration. A several-year trend in increasing abundance inferred by increasing CPUE would generally be expected to be accompanied by decreasing exploitation rates and increasing average weights. The purse-seine catch has been increasing since 1985, and is currently above the upper reference level (Figure 9).

The results of the simple stock assessment model are similar to those of the most recent stock assessment (compare Figures 3 and 10). The estimates of the average length of the fish of the youngest age group (48 cm) and the annual survival rate (0.25) are consistent with current knowledge of the skipjack fishery of the EPO, bearing in mind that the length of the youngest age group is the length at entry to the fishery, not the length at age 1. The numbers in the plus group (age 4) in the initial population in 1975 was very poorly estimated. The fit to all three data sets was reasonable (Figure 10). However, there were some runs in the residuals, as is common in most stock assessments. The biomass is highly driven by the recruitment, and both show an increase in recent years. The exploitation rate was estimated to have increased since the middle of the time frame, and was constrained by the 0.9 maximum in one year. After 2001, the estimated CPUE and exploitation rate increased while average weight decreased, as do the indicators.

4. DISCUSSION

Comparison of multiple indices based on relative values compared to historical levels provides a method to evaluate the status of the EPO skipjack tuna stock in the absence of traditional reference points. However, this method does not provide any information on optimizing yields (*e.g.* MSY quantities). Similar approaches have been applied to other stocks: for example, Trenkel *et al.* (2007) applied a somewhat more comprehensive approached based on survey data. Rather than using reference lines, they used hypothesis tests on the slope of the indicator. They used trends because they can be estimated more reliably than absolute values. They also suggest that the results of several indicators be combined to provide management advice.

Average weight is influenced by both exploitation rate and recruitment. For example, a large recruitment entering the fishery would cause the average weight to initially decline, but then increase as that cohort moved through the fishery. However, for illustrative purposes, if recruitment were constant, higher exploitation rates would reduce the average weight. Therefore, it is important to differentiate between changes in average weight due to recruitment and due to exploitation rate. If effort is relatively constant over time, then fluctuations in average weight are probably due to fluctuations in recruitment. Long-term trends in average weight could be due to increasing or decreasing exploitation rates. However, this may be confounded by changes in selectivity. The average weight for skipjack has large cyclic fluctuations, which appear to be correlated with environmental conditions (*e.g.* with El Niño events; R-square = 0.26), but there does not appear to be any trend.

There is a contradiction between the recent CPUE increase and the changes in the standardized effort (increase) and average weight (decrease) indicators for skipjack in the EPO. This is true even when the one-year lag for average weight is taken into consideration. The CPUE has generally been increasing since 2000, while the average weight and standardized effort have generally been decreasing. However, the low average weight in 2006 may indicate a strong recruitment, which would translate into high CPUE and catch in 2007 . The results of applying the simple stock assessment model fit to both CPUE and average weight suggest that the inconsistency can be explained by a parallel increase in both exploitation rate and abundance. However, indicators for both exploitation rate and abundance are close to or above their upper reference levels, providing contradictory management advice. An alternative explanation is an increase in the catchability of the purse-seine fisheries. This hypothesis is consistent with the flat index of abundance developed by Maunder and Hoyle (2007), using a novel method based on ratios of skipjack to bigeye in catch from the floating-object fisheries, which may be robust to changes in catchability.

If the indicator approach is adopted, a link between the indicator and management action should be made. The action could be quite explicit, for example, if CPUE declines below the lower level, the effort would be reduced by a given amount, or it could just trigger a more comprehensive analysis of the stock. Due to the short life span of skipjack, management might be appropriate on a scale of less than one year, which would be facilitated by an indicator-based approach.

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TABLE 1. Status of the stock based on when reference levels are exceeded for each indicator

Indicator	Lower reference level	Upper reference level
CPUE	Undesirable	Healthy, but may be due to increased catchability
Average weight	Undesirable, but may be due to large recruitment	Healthy, but may be due to poor recruitment
Effort	Healthy	Undesirable
Catch	Ambiguous	Ambiguous

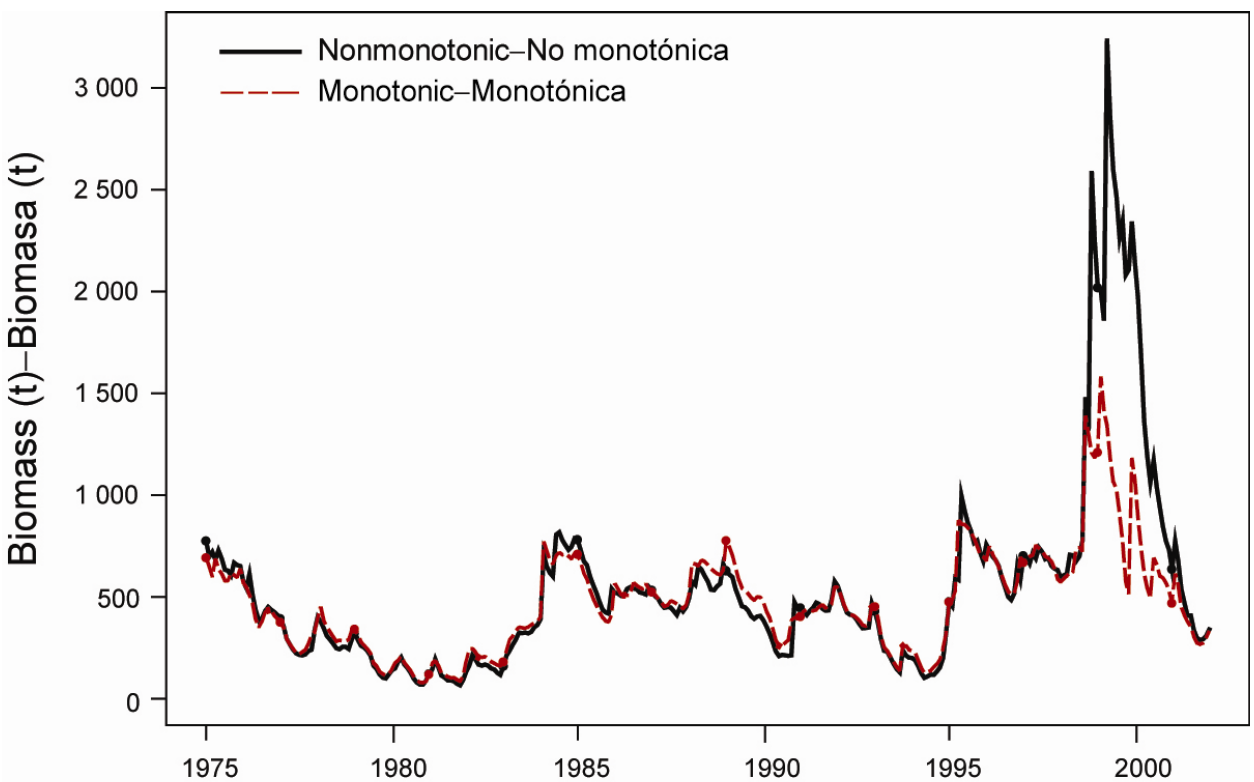

FIGURE 1. Comparison of estimated biomass between the assessments with monotonic and nonmonotonic selectivity from the 2002 assessment (Maunder 2002).

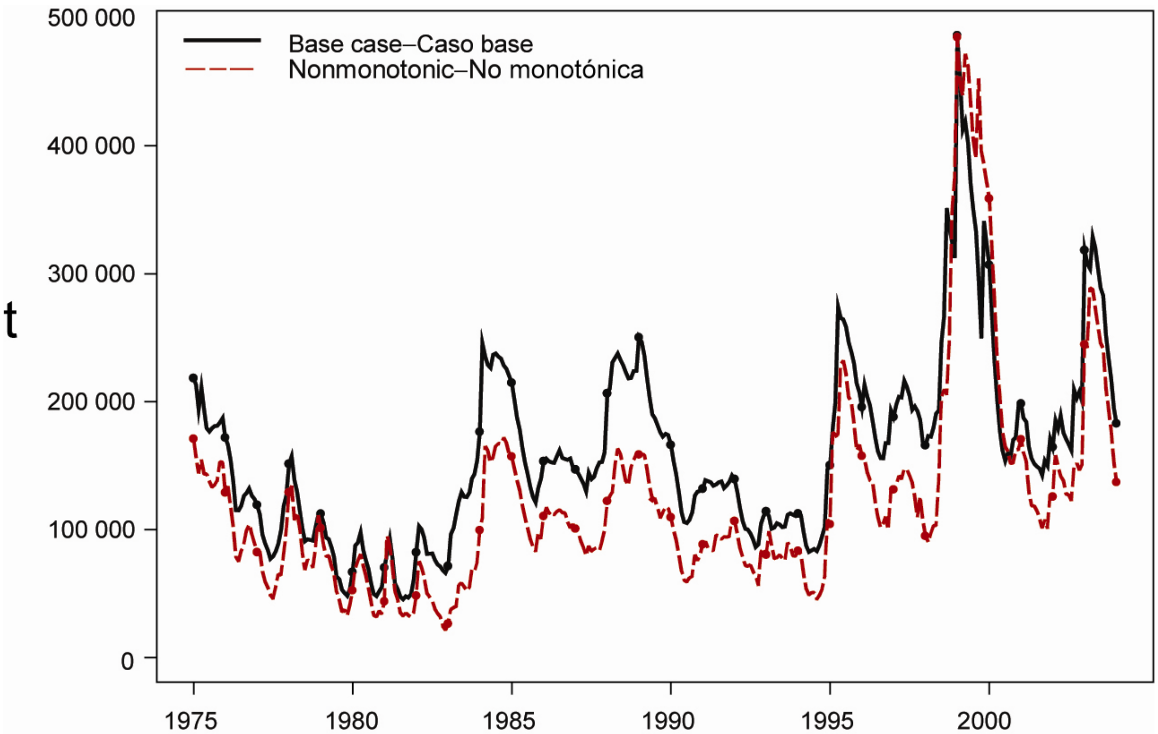

FIGURE 2. Comparison of estimated biomass between the base case assessment, which assumes monotonic selectivity, with the sensitivity analysis that uses nonmonotonic selectivity from the 2004 assessment (Maunder and Harley 2005).

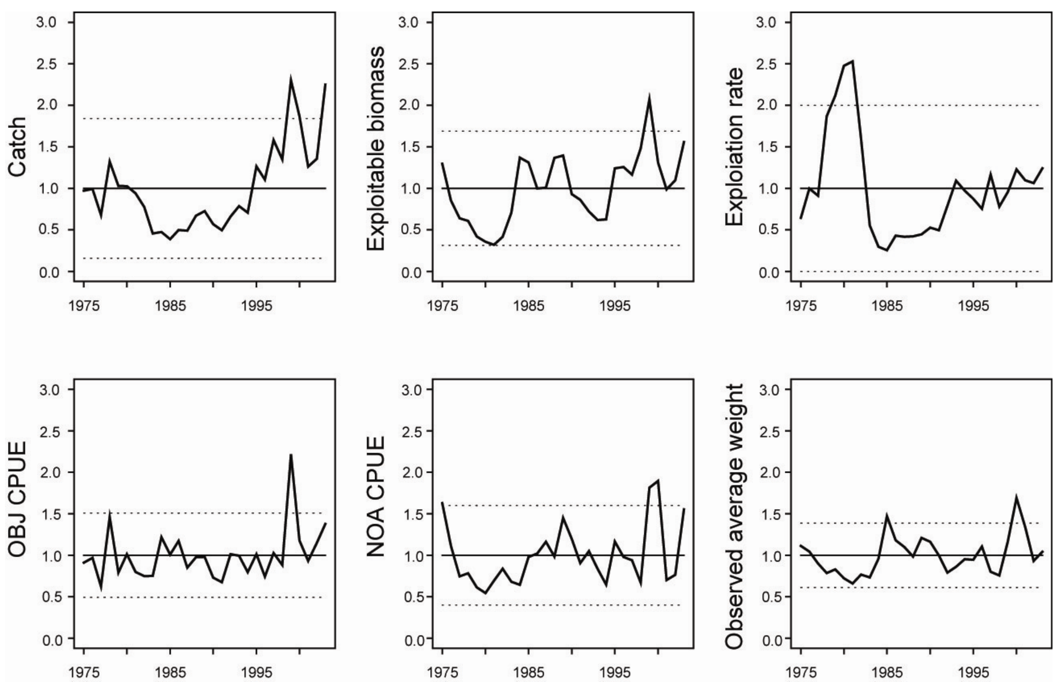

FIGURE 3. Indicators of stock status for skipjack tuna compared to estimates of exploitable biomass and exploitation rate from the 2004 assessment (Maunder and Harley 2005). The horizontal dashed lines represent ± 1.645 standard deviations from the means.

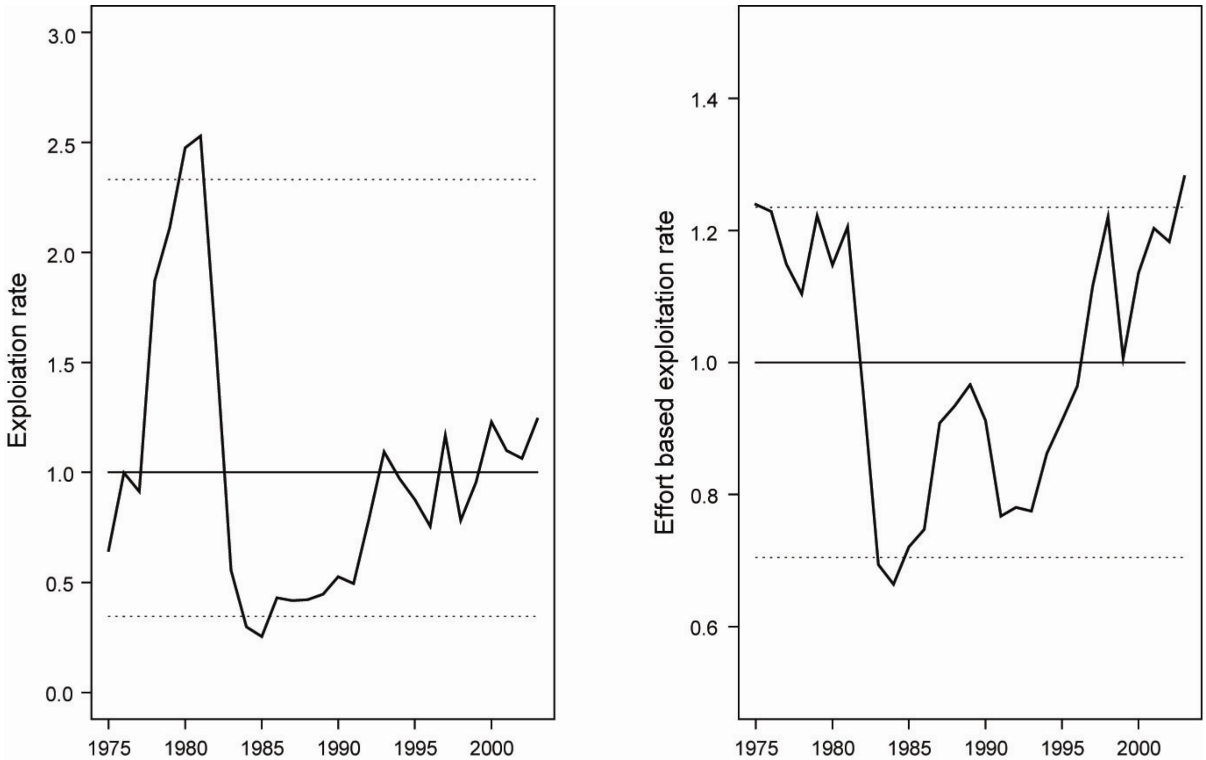

FIGURE 4. Exploitation rate estimated by the most recent stock assessment (left) and represented by standardized effort (right). The horizontal dashed lines represent the 5th and 95th percentiles.

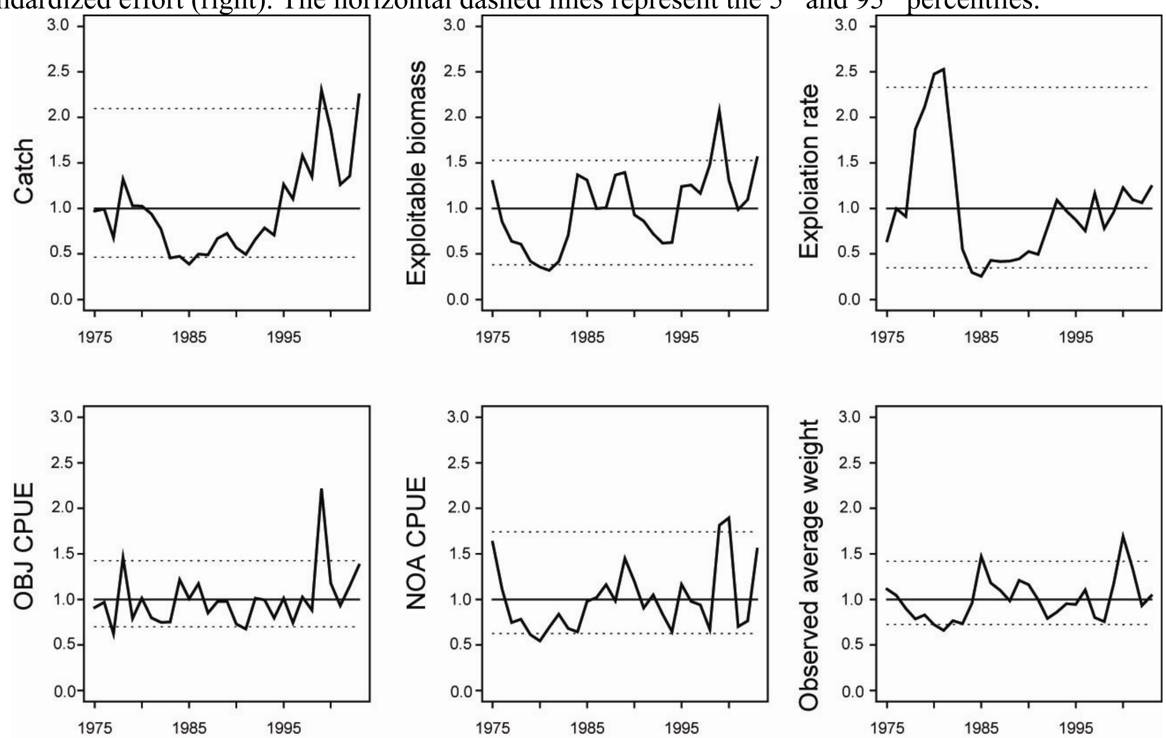

FIGURE 5. Indicators of stock status for skipjack tuna compared to estimates of exploitable biomass and exploitation rate from the 2004 assessment (Maunder and Harley 2005). The horizontal dashed lines represent the 5th and 95th percentiles. OBJ: floating object; NOA: unassociated.

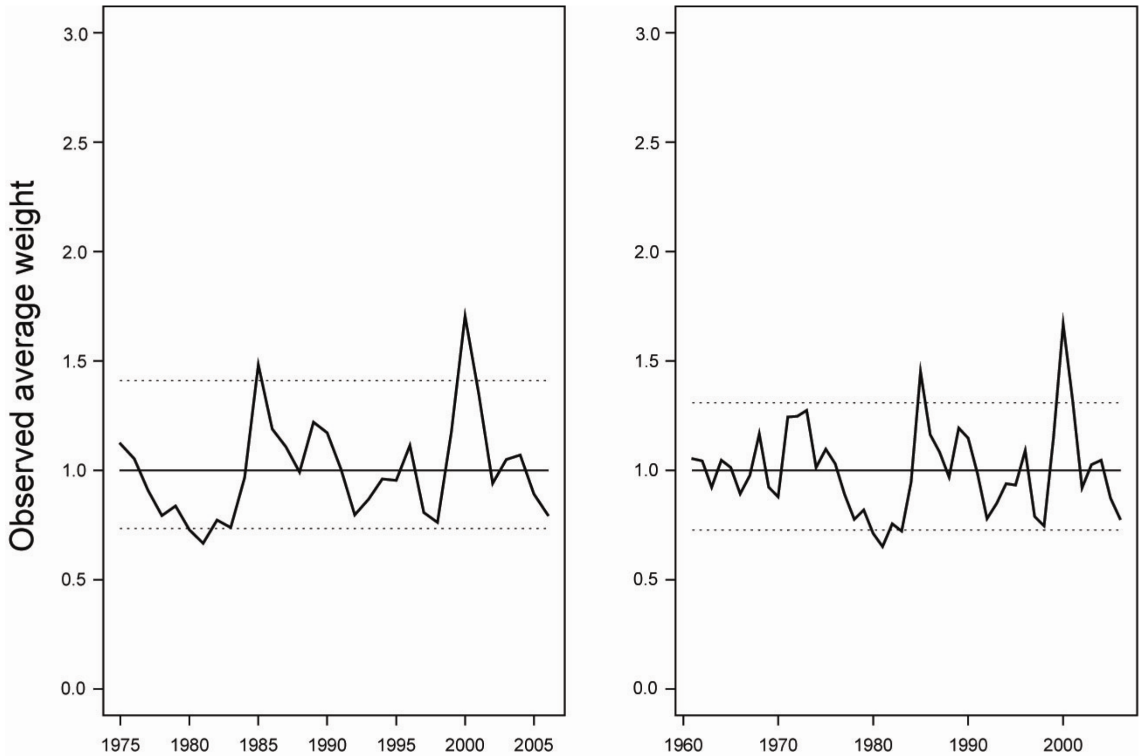

FIGURE 6. Average weight for skipjack tuna scaled so the average equals one over different periods. The average weight scaling and reference lines are based on 1975-2006 (left) and 1961-2006 (right). The horizontal dashed lines represent the 5th and 95th percentiles.

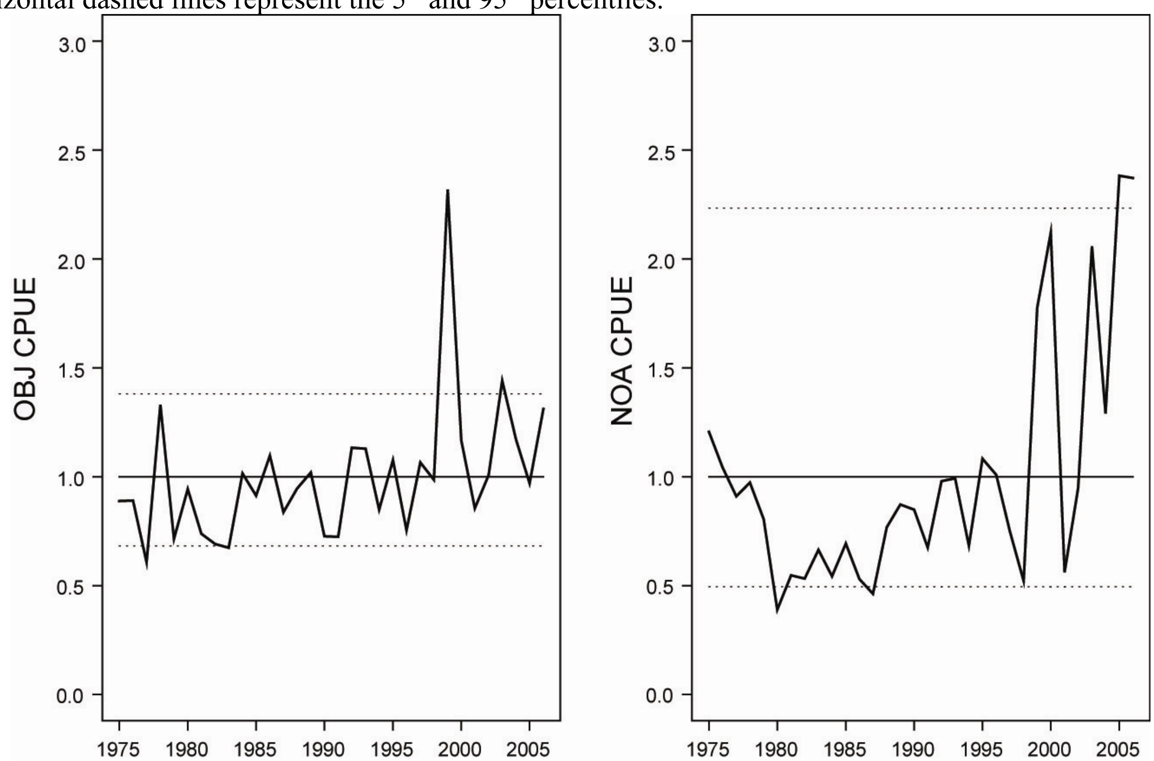

FIGURE 7. Floating object (OBJ) and unassociated (NOA) purse-seine CPUE for skipjack tuna. The horizontal dashed lines represent the 5th and 95th percentiles.

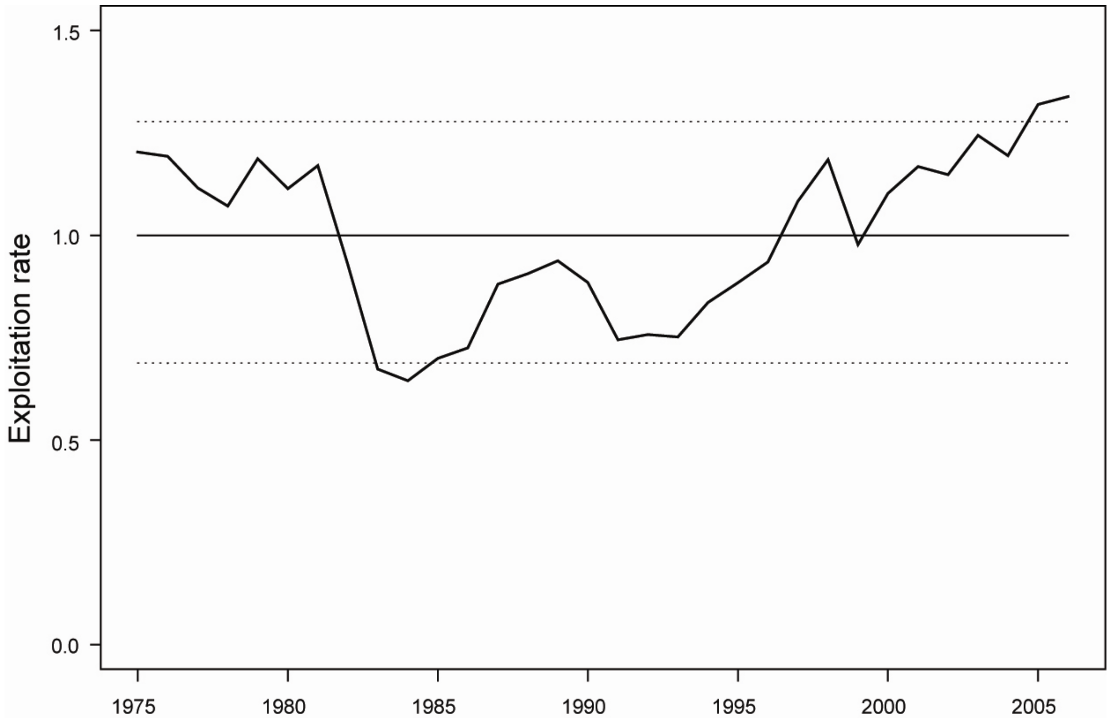

FIGURE 8. Exploitation rate indicator based on standardized effort. The horizontal dashed lines represent the 5th and 95th percentiles.

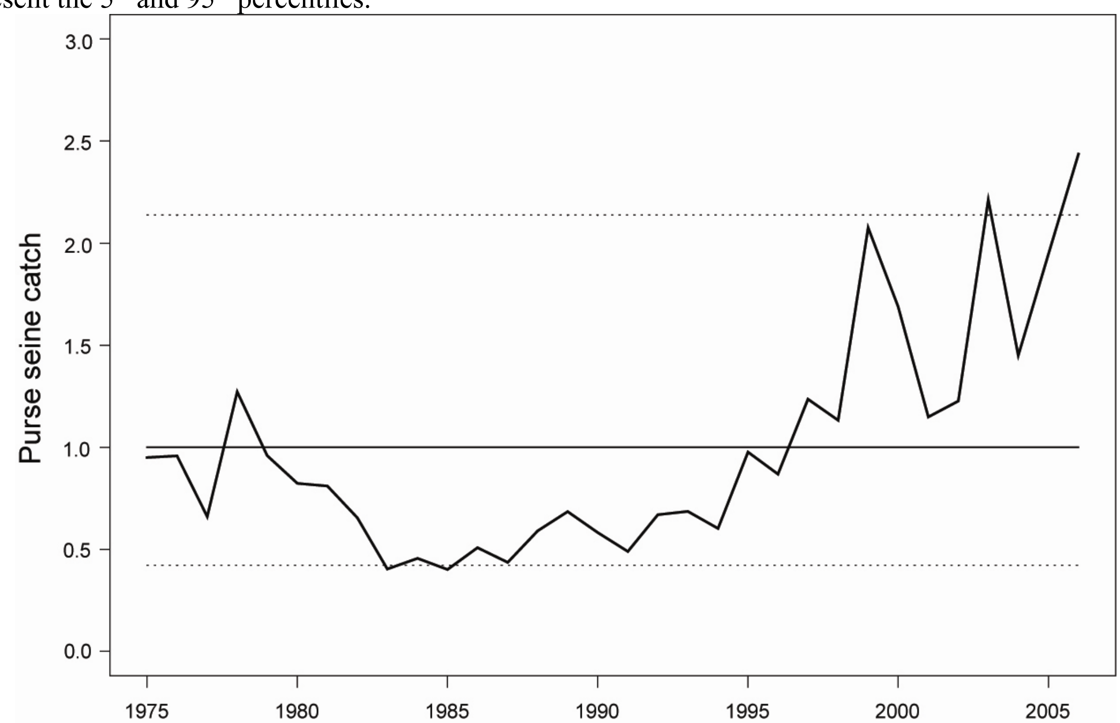

FIGURE 9. Relative purse-seine catch of skipjack tuna. The horizontal dashed lines represent the 5th and 95th percentiles.

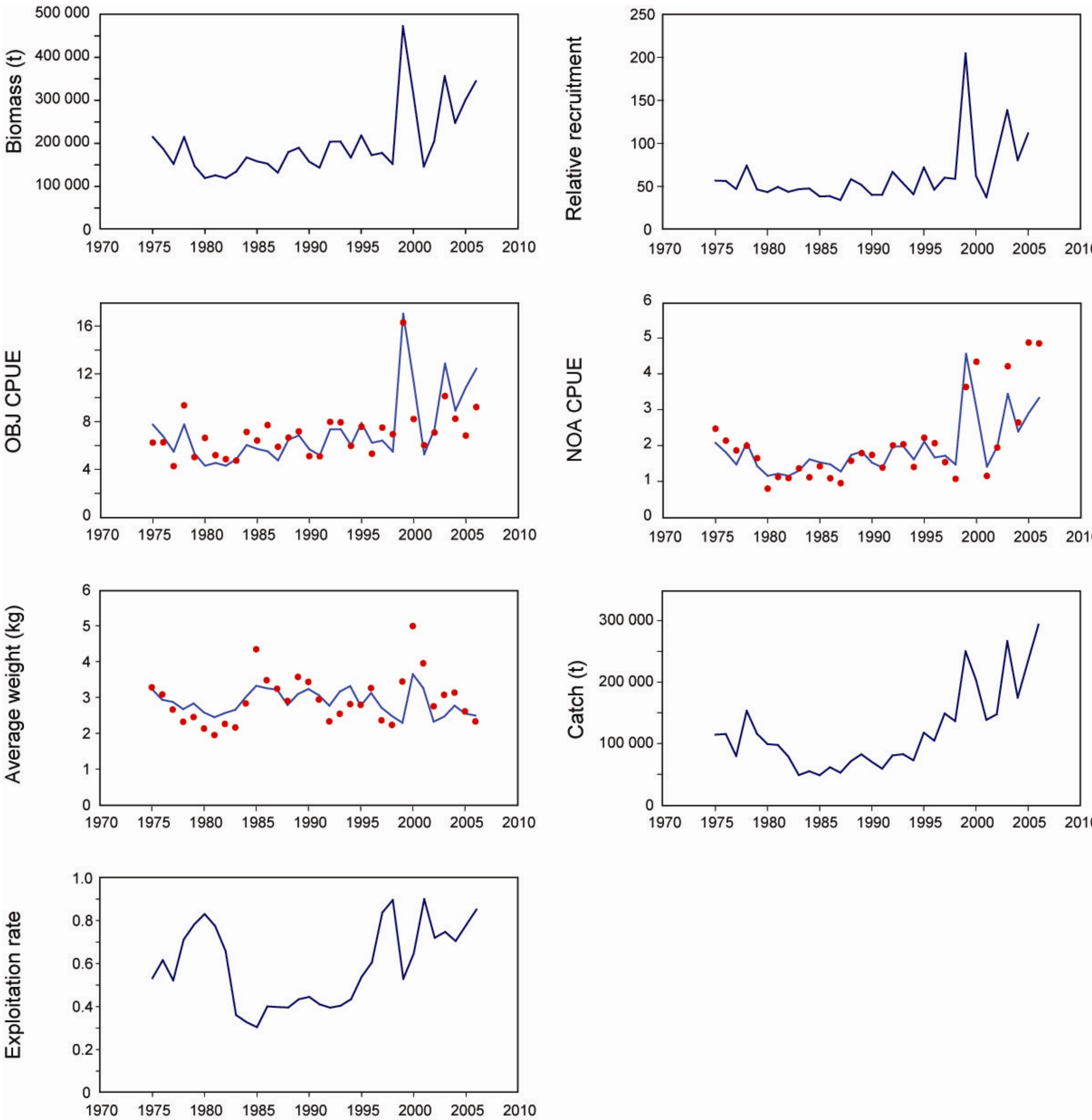

FIGURE 10. Results from the simple stock assessment model fit to CPUE and average weight (kg) data for skipjack tuna in the EPO. OBJ: floating object; NOA: unassociated.

Appendix

SIMPLE STOCK ASSESSMENT MODEL FIT TO CPUE AND AVERAGE WEIGHT DATA

1. DYNAMICS

$N_{1,a} = N_{init,a}$ a > 1

$N_{t,1} = R_t$

$R_t = R_{ave} \exp\left[\sigma_R \varepsilon_t - 0.5\sigma_R^2\right]$

$N_{t+1,a+1} = \phi(1-u_t)N_{t,a}$

$N_{t+1,A} = \phi(1-u_t)\left(N_{t,A-1} + N_{t,A}\right)$

$L_a = L_{a-1} + \left(L_\infty - L_{a-1}\right)\left(1-\exp[-K]\right)$

$w_a = \alpha L_a^\beta$

$B_t = \sum_a N_{t,a} w_a$

$u_t = \frac{C_t}{B_t}$

2. LIKELIHOODS

CPUE

$$\ln L\left(\theta \mid I_t^{CPUE}\right) = \ln\left(\sigma_{CPUE}\right) + \frac{\left(\ln\left(I_t^{CPUE}\right) - \ln\left(q_{CPUE} B_t\right)\right)^2}{2\sigma_{CPUE}^2}$$

$$q_{CPUE} = \exp\left[\frac{\sum_t \left(\ln\left(I_t^{CPUE} / B_t\right)\right)}{T}\right]$$

Average weight

$$\ln L\left(\theta \mid I_t^w\right) = \ln\left(\sigma_w\right) + \frac{\left(\ln\left(I_t^w\right) - \ln\left(q_w \overline{w}_t\right)\right)^2}{2\sigma_w^2}$$

$$\overline{w}_t = \frac{B_t}{\sum_a N_{t,a}}$$

Recruitment deviates

$$\ln p(\varepsilon) = 0.5 \sum_t \varepsilon_t^2$$

R_t	Recruitment at time t
$N_{t,a}$	Number of individuals at time t in age group a

σ_R	Standard deviation of recruitment variation
R_{ave}	Average recruitment
ε_t	Recruitment deviate for time t
ϕ	Annual survival
u_t	Exploitation rate at time t
L_a	Length at age a
L_∞	Asymptotic length parameter of the von Bertalanffy growth curve
K	Growth rate parameter of the von Bertalanffy growth curve
w_a	Weight at age a
α	Scaling parameter of the weight-length relationship
β	Exponential parameter of the weight-length relationship
B_t	Exploitable biomass in time t
C_t	Catch in time t
I_t^{CPUE}	CPUE index of abundance in year t
q_{CPUE}	Catchability coefficient for the CPUE index of abundance
σ_{CPUE}	Standard deviation for the CPUE index of abundance likelihood.
$\overline{w}_t$	Model-estimated average weight in time t
I_t^w	Observed average weight in year t
q_w	Scaling coefficient for the average weight
σ_w	Standard deviation for the average weight likelihood.

3. PARAMETERS

Estimated

$$\left(N_{init,2}, N_{init,3}, \ldots, N_{init,A}, R_{ave}, \varepsilon_1, \varepsilon_2, \ldots, \varepsilon_T, \phi, L_1\right)$$

Fixed

L_∞ = 84.6 cm

$K = 0.8$

$\alpha = 0.5529\text{e-}5$

$\beta = 3.336$

$q_w = 1$

$\sigma_w = \sigma_{FO} = \sigma_{UA} = 0.3$

$\sigma_R = 1.0$

Given

A=4

Data

TABLE A.1 Data used in the population dynamics model.

Year	Catch (t)	Floating object CPUE	Unassociated CPUE	Average weight (kg)
1975	114463.1	6.242616	2.465743	3.28
1976	115458.1	6.257607	2.13326	3.08
1977	79538.29	4.271756	1.861175	2.66
1978	153161.7	9.354834	1.990595	2.32
1979	115545.2	5.022688	1.64661	2.45
1980	99158.98	6.630887	0.796648	2.13
1981	97543.45	5.192427	1.119234	1.95
1982	78778.95	4.855562	1.089544	2.26
1983	48613.68	4.736024	1.357964	2.16
1984	54956.11	7.132496	1.110767	2.83
1985	48310.95	6.41627	1.418516	4.34
1986	61270.84	7.70538	1.083907	3.48
1987	52559.17	5.882939	0.94589	3.24
1988	71167.13	6.649494	1.571733	2.9
1989	82485.29	7.16745	1.785012	3.57
1990	70208.4	5.108285	1.735528	3.43
1991	58990.79	5.091252	1.381237	2.94
1992	80665.39	7.966732	2.003764	2.33
1993	82680.8	7.938567	2.030923	2.54
1994	72610.76	5.964477	1.397775	2.81
1995	117564.8	7.567107	2.213897	2.79
1996	104591.9	5.307022	2.063543	3.26
1997	148792.7	7.489617	1.534416	2.36
1998	136413.7	6.932917	1.067756	2.23
1999	250157.4	16.29459	3.631185	3.44
2000	203485.5	8.208242	4.334591	4.99
2001	138358.1	6.015368	1.147852	3.95
2002	147683.9	7.081583	1.941171	2.75
2003	266650.9	10.13005	4.208462	3.07
2004	174642.8	8.231198	2.639629	3.13
2005	234567.4	6.820856	4.871742	2.61
2006	293495.7	9.217152	4.848166	2.33